

# DENOMINATORS IN CLUSTER ALGEBRAS OF AFFINE TYPE

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ABSTRACT. The Fomin-Zelevinsky *Laurent phenomenon* states that every cluster variable in a cluster algebra can be expressed as a Laurent polynomial in the variables lying in an arbitrary initial cluster. We give representation-theoretic formulas for the denominators of cluster variables in cluster algebras of affine type. The formulas are in terms of the dimensions of spaces of homomorphisms in the corresponding cluster category, and hold for any choice of initial cluster.

## INTRODUCTION

Cluster algebras were introduced by Fomin and Zelevinsky in [FZ1]. They have strong links with the representation theory of finite dimensional algebras (see e.g. the survey articles [BM, K2]), with semisimple algebraic groups and the dual semicanonical basis of a quantum group (see e.g. the survey article [GLS]), and with many other areas (see e.g. the survey article [FZ2]); these articles contain many further references.

Here we consider acyclic coefficient-free cluster algebras of affine type, i.e. those which can be given by an extended Dynkin quiver. We give a formula expressing the denominators of cluster variables in terms of any given initial cluster in terms of dimensions of certain Hom-spaces in the corresponding cluster category. The representation theory, and hence the cluster category, is well understood in the tame case. Thus, the formula can be used to compute the denominators explicitly.

We assume that  $k$  is an algebraically closed field. Caldero and Keller [CK2] (see also [BCKMRT]) have shown, using the Caldero-Chapoton map [CC], that for an acyclic quiver  $Q$ , the cluster variables of the acyclic cluster algebra  $\mathcal{A}_Q$  are in bijection with the indecomposable exceptional objects in the cluster category  $\mathcal{C}_H$ , where  $H = kQ$  is the path algebra of  $Q$ . Furthermore, under this correspondence the clusters correspond to cluster-tilting objects. We denote by  $x_M$  the cluster variable corresponding to the exceptional indecomposable  $M$  in  $\mathcal{C}_{kQ}$ .

Recall that an indecomposable regular  $H$ -module  $X$  lies in a connected component of the AR-quiver of  $H$  known as a tube, which we denote by  $\mathcal{T}_X$ . For a regular indecomposable exceptional module  $X$ , we let  $\mathcal{W}_X$  denote the

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wing of  $X$  inside  $\mathcal{T}_X$ , i.e. the category of subfactors of  $X$  inside  $\mathcal{T}_X$ . We let  $\tau$  denote the Auslander-Reiten translate.

We prove the following theorem.

**Theorem A.** *Let  $Q$  be an extended Dynkin quiver. Let  $H$  be the path algebra of a  $Q$ , and let  $\{y_1, \dots, y_n\} = \{x_{\tau T_1}, \dots, x_{\tau T_n}\}$  be an arbitrary initial seed of the cluster algebra  $\mathcal{A}_Q$ , where  $T = \coprod_i T_i$  is a cluster-tilting object in  $\mathcal{C}_{kQ}$ . Let  $X$  be an exceptional object of  $\mathcal{C}$  not isomorphic to  $\tau T_i$  for any  $i$ . Then, in the expression  $x_X = f/m$  in reduced form we have  $m = \prod_i y_i^{d_i}$ , where*

$$d_i = \begin{cases} \dim \operatorname{Hom}_{\mathcal{C}}(T_i, X) - 1 & \text{if there is a tube of rank } t \geq 2 \text{ containing } T_i \text{ and } X, \text{ q.l. } T_i = t - 1 \text{ and } X \notin \mathcal{W}_{\tau T_i}, \\ \dim \operatorname{Hom}_{\mathcal{C}}(T_i, X) & \text{otherwise.} \end{cases}$$

We remark that representation-theoretic expressions for denominators of cluster variables for an arbitrary initial seed were given in [CCS1] for type A and for any simply-laced Dynkin quiver in [CCS2, RT]. In the general case, for an initial seed with acyclic exchange quiver, it was shown in [BMRT, CK2] that denominators of cluster variables are given by dimension vectors (see the next section for more details). The general case for an arbitrary initial seed was studied in [BMR2]. In particular, it was shown that for an affine cluster algebra, provided the cluster-tilting object corresponding to the initial seed contains no regular summand of maximal quasilength in its tube, the denominators of all cluster variables are given by dimension vectors. Cluster variables in affine cluster algebras of rank 2 have been studied in [CZ, MP, SZ, Ze]. The present article completes the denominator picture (for an arbitrary initial seed), in terms of dimension vectors, for affine (coefficient-free) cluster algebras.

In [FK, 5.6] it is shown that for any cluster category (and in fact in a wider context), the dimension vector of a module coincides with the corresponding  $f$ -vector in the associated cluster algebra with principal coefficients. Thus our results determine when Conjecture 7.17 of [FZ3] holds for affine cluster algebras. We also remark that in Theorem A, each exponent in the denominator is less than or equal to the corresponding entry in the dimension vector, in agreement with [FK, 5.8] and [DWZ].

Representation-theoretic expressions for cluster variables have been widely studied; see for example [BKL, CK1, D, Hu, M, Pal, Par, Pr, S, ST, YZ, XX1, XX2, XX3, Zh]. See in particular [BKL, D] for other aspects of cluster combinatorics associated with tubes.

In Section 1, we recall some of the results described in the previous paragraph. In Section 2, we recall some standard facts about tame hereditary algebras. In Section 3, we show that, in order to prove Theorem A for every indecomposable object in  $\mathcal{C}$  which is not regular it is sufficient to prove this holds for the summands of a single cluster-tilting object with no regular summands. In Section 4, we study regular objects in the cluster category, and then in Section 5 we prove the main theorem, and in Section 6 we give a small example to illustrate it.

## 1. PRELIMINARIES

Let  $Q$  be a finite connected acyclic quiver and  $k$  an algebraically closed field. Then  $H = kQ$  denotes the (finite dimensional) path algebra of  $Q$  over  $k$ . Let  $D^b(H)$  be the bounded derived category of finite dimensional left  $H$ -modules. The category  $D^b(H)$  is a triangulated category with a suspension functor  $[1]$  (the shift). Since  $H$  is hereditary, the category  $D^b(H)$  has almost split triangles; see [Ha], and thus has an autoequivalence  $\tau$ , the Auslander-Reiten translate. Let  $\mathcal{C} = \mathcal{C}_H = D^b(H)/\tau^{-1}[1]$  be the cluster category of  $H$  (introduced in [CCS1] for type  $A$  and in [BMRRT] in general). Keller [K1] has shown that  $\mathcal{C}$  is triangulated. For more information about the representation theory of finite dimensional algebras, see [ARS, ASS], and see [Ha] for basic properties of derived categories.

We regard  $H$ -modules as objects of  $\mathcal{C} = \mathcal{C}_H$  via the natural embedding of the module category of  $H$  in  $D^b(H)$ . For a vertex  $i$  of  $Q$ , let  $P_i$  denote the corresponding indecomposable projective  $H = kQ$ -module. Note that every indecomposable object of  $\mathcal{C}$  is either an indecomposable  $H$ -module or of the form  $P_i[1]$  for some  $i$ .

We denote homomorphisms in  $\mathcal{C}$  simply by  $\text{Hom}(\ , \ )$ , while  $\text{Hom}_H(\ , \ )$  denotes homomorphisms in  $\text{mod } H$  (or  $D^b(H)$ ). For a fixed  $H$ , we say that a map  $X \rightarrow Y$  in  $\mathcal{C}_H$  is an  $F$ -map if it is induced by a map  $X \rightarrow \tau^{-1}Y[1]$  in  $D^b(H)$ , where  $X, Y$  are direct sums of  $H$ -modules or objects of the form  $P_i[1]$ . Note that the composition of two  $F$ -maps is zero.

An  $H$ -module  $T$  is called a *partial tilting module* if  $\text{Ext}_H^1(T, T) = 0$ , an *almost complete tilting module* if in addition it has  $n - 1$  nonisomorphic indecomposable summands, and a *tilting module* if it has  $n$  such summands (by a result of Bongartz [Bo] this is equivalent to the usual notion of a tilting module over  $H$ ). We shall assume throughout that all such modules are *basic*, i.e. no indecomposable summand appears with multiplicity greater than 1. For more information on tilting theory see [AHK].

The corresponding notions of *cluster-tilting object*, *partial cluster-tilting object* and *almost complete cluster-tilting object* in  $\mathcal{C}$  can be defined similarly with reference to the property  $\text{Ext}_{\mathcal{C}}^1(T, T) = 0$ ; see [BMRRT]. Note that every cluster-tilting object in  $\mathcal{C}$  is induced from a tilting module over some hereditary algebra derived equivalent to  $H$  [BMRRT, 3.3].

Let  $\mathcal{A} = \mathcal{A}(Q) \subseteq \mathbb{F} = \mathbb{Q}(x_1, x_2, \dots, x_n)$  be the (acyclic, coefficient-free) cluster algebra defined using the initial seed  $(\mathbf{x}, Q)$ , where  $\mathbf{x}$  is a free generating set  $\{x_1, x_2, \dots, x_n\}$  for  $\mathbb{F}$ ; see [FZ1].

For an object  $X$  of  $\mathcal{C}$ , let  $c_X = \prod_{i=1}^n x_i^{\dim \text{Hom}_{\mathcal{C}}(P_i, X)}$ . The following gives a connection between cluster categories and acyclic cluster algebras.

**Theorem 1.1.** (a) [BMRT, 2.3] *There is a surjective map*

$$\alpha: \{\text{cluster variables of } \mathcal{A}(Q)\} \rightarrow \{\text{indecomposable exceptional objects in } \mathcal{C}\}.$$

*It induces a surjective map*

$$\bar{\alpha}: \{\text{clusters}\} \rightarrow \{\text{cluster-tilting objects}\},$$

*and a surjective map*

$$\tilde{\alpha}: \{\text{seeds}\} \rightarrow \{\text{tilting seeds}\},$$

preserving quivers.

(b) [CK2] There is a bijection  $\beta: X \rightarrow x_X$  from indecomposable exceptional objects of  $\mathcal{C}$  to cluster variables of  $\mathcal{A}$  such that for any indecomposable exceptional  $kQ$ -module  $X$ , we have  $x_X = f/c_X$  as an irreducible quotient of integral polynomials in the  $x_i$ , where  $c_X = \prod_{i=1}^n x_i^{\dim \text{Hom}_{\mathcal{C}}(P_i, X)}$ .

(c) [BCKMRT] The maps  $\alpha$  and  $\beta$  are mutual inverses.

We now recall some results and definitions from [BMR2]. Assume  $\Gamma$  is a quiver which is mutation-equivalent to  $Q$ . By the above theorem there is a seed  $(\mathbf{y}, \Gamma)$  of  $\mathcal{A}$ , where  $\mathbf{y} = \{y_1, y_2, \dots, y_n\}$  is a free generating set of  $\mathbb{F}$  over  $\mathbb{Q}$ . Let  $T_i = \tau^{-1}\alpha(y_i)$  for  $i = 1, 2, \dots, n$ , so that we have  $\alpha(y_i) = \tau T_i$ . Then  $\prod_{i=1}^n \tau T_i$  is a cluster-tilting object in  $\mathcal{C}$  and  $\Gamma$  is the quiver of  $\text{End}_{\mathcal{C}}(\tau T)^{\text{op}} \simeq \text{End}_{\mathcal{C}}(T)^{\text{op}}$  by [BMR1].

**Definition 1.2.** [BMR2] Let  $x$  be a cluster variable of  $\mathcal{A}$ . We say that  $x$  expressed in terms of the cluster  $\mathbf{y}$  has a  $T$ -denominator if either:

- (I) We have that  $\alpha(x) = X$  for some exceptional indecomposable object  $X$  of  $\mathcal{C}$  not isomorphic to  $\tau T_i$  for any  $i$ , and  $x = f/t_X$ , where  $t_X = \prod_{i=1}^n y_i^{\dim \text{Hom}_{\mathcal{C}}(T_i, X)}$ , or
- (II) We have that  $\alpha(x) = \tau T_i$  for some  $i$  and  $x = y_i$ .

Here, in addition, we make the following definition:

**Definition 1.3.** A regular object  $X$  of  $\mathcal{C}$  has a reduced  $T$ -denominator if  $d_i = \dim \text{Hom}_{\mathcal{C}}(T_i, X) - 1$  for all regular summands  $T_i$  of  $T$  with  $\mathcal{T}_X = \mathcal{T}_{T_i}$  and  $d_j = \dim \text{Hom}_{\mathcal{C}}(T_j, X)$  for all other summands  $T_j$ .

**Theorem 1.4.** [BMR2] Let  $T = \prod_{i=1}^n T_i$  be a cluster-tilting object in  $\mathcal{C} = \mathcal{C}_{kQ}$  for an acyclic quiver  $Q$  and let  $\mathcal{A} = \mathcal{A}(Q)$  be the cluster algebra associated to  $Q$ . Then:

- (a) If no indecomposable direct summand of  $T$  is regular then every cluster variable of  $\mathcal{A}$  has a  $T$ -denominator.
- (b) If every cluster variable of  $\mathcal{A}$  has a  $T$ -denominator, then  $\text{End}_{\mathcal{C}}(T_i) \simeq k$  for all  $i$ .

Suppose in addition that  $kQ$  is a tame algebra. Then the following are equivalent:

- (i) Every cluster variable of  $\mathcal{A}$  has a  $T$ -denominator.
- (ii) No regular summand  $T_i$  of quasi-length  $r - 1$  lies in a tube of rank  $r$ .
- (iii) For all  $i$ ,  $\text{End}_{\mathcal{C}}(T_i) \simeq k$ .

The main result (Theorem A) of this paper gives a precise description of the denominators of all cluster variables for the tame case, i.e. also including the case when  $T$  has a regular summand  $T_i$  of quasi-length  $r - 1$  lying in a tube of rank  $r$ .

Fix an almost complete (basic) cluster-tilting object  $\overline{T}'$  in  $\mathcal{C}$ . Let  $X, X^*$  be the two complements of  $\overline{T}'$ , so that  $T' = \overline{T}' \amalg X$  and  $T'' = \overline{T}' \amalg X^*$  are cluster-tilting objects (see [BMRRT, 5.1]). Let

$$X^* \xrightarrow{f} B \xrightarrow{g} X \xrightarrow{h} \quad (1)$$

$$X \xrightarrow{f'} B' \xrightarrow{g'} X^* \xrightarrow{h'} \quad (2)$$

be the exchange triangles corresponding to  $X$  and  $X^*$  (see [BMRRT, §6]), so that  $B \rightarrow X$  is a minimal right  $\text{add}(\overline{T}')$ -approximation of  $X$  in  $\mathcal{C}$  and  $B' \rightarrow X^*$  is a minimal right  $\text{add}(\overline{T}')$ -approximation of  $X^*$  in  $\mathcal{C}$ . The following definition is crucial:

**Definition 1.5.** [BMR2] *Let  $M$  be an exceptional indecomposable object of  $\mathcal{C}$ . We say that  $M$  is compatible with an exchange pair  $(X, X^*)$ , if either  $X \simeq \tau M$ ,  $X^* \simeq \tau M$ , or, if neither of these holds,*

$$\begin{aligned} \dim \text{Hom}_{\mathcal{C}}(M, X) + \dim \text{Hom}_{\mathcal{C}}(M, X^*) \\ = \max(\dim \text{Hom}_{\mathcal{C}}(M, B), \dim \text{Hom}_{\mathcal{C}}(M, B')). \end{aligned}$$

*If  $M$  is compatible with every exchange pair  $(X, X^*)$  in  $\mathcal{C}$  we call  $M$  exchange compatible.*

We also have:

**Proposition 1.6.** [BMR2]

- (a) *Suppose that  $(X, X^*)$  is an exchange pair such that neither  $X$  nor  $X^*$  is isomorphic to  $\tau M$ . Then the following are equivalent:*
  - (i)  *$M$  is compatible with the exchange pair  $(X, X^*)$ .*
  - (ii) *Either the sequence*

$$0 \rightarrow \text{Hom}_{\mathcal{C}}(M, X^*) \rightarrow \text{Hom}_{\mathcal{C}}(M, B) \rightarrow \text{Hom}_{\mathcal{C}}(M, X) \rightarrow 0 \quad (3)$$

*is exact, or the sequence*

$$0 \rightarrow \text{Hom}_{\mathcal{C}}(M, X) \rightarrow \text{Hom}_{\mathcal{C}}(M, B') \rightarrow \text{Hom}_{\mathcal{C}}(M, X^*) \rightarrow 0 \quad (4)$$

*is exact.*

- (b) *Let  $M$  be an exceptional indecomposable object of  $\mathcal{C}$  and suppose that  $X \simeq \tau M$  or  $X^* \simeq \tau M$ . Then we have that*

$$\begin{aligned} \dim \text{Hom}_{\mathcal{C}}(M, X) + \dim \text{Hom}_{\mathcal{C}}(M, X^*) = \\ \max(\dim \text{Hom}_{\mathcal{C}}(M, B), \dim \text{Hom}_{\mathcal{C}}(M, B')) + 1 \end{aligned}$$

- (c) *Let  $(\mathbf{x}', Q')$  be a seed, with  $\mathbf{x}' = \{x'_1, \dots, x'_n\}$ , and assume that each  $x'_i$  has a  $T$ -denominator. Let  $T'_i = \alpha(x'_i)$  for  $i = 1, 2, \dots, n$  and  $T' = \prod_{j=1}^n T'_j$ . Mutating  $(\mathbf{x}', Q')$  at  $x'_k$  we obtain a new cluster variable  $(x'_k)^*$ . Let  $\overline{T}' = \prod_{j \neq k} T'_j$ . and let  $X^*$  be the unique indecomposable object in  $\mathcal{C}$  with  $X^* \not\simeq T'_k = X$  such that  $\overline{T}' \amalg X^*$  is a cluster-tilting object. Then the cluster variable  $x_{X^*} = (x'_k)^*$  has a  $T$ -denominator if each summand  $T_i$  of  $T$  is compatible with the exchange pair  $(X, X^*)$ .*

Note that (c) is used as an induction step in [BMR2] for showing that cluster variables have  $T$ -denominators. Also, in [BMR2] it is shown that in (c) the cluster variable  $x_{X^*} = (x'_k)^*$  has a  $T$ -denominator if and only if each summand  $T_i$  of  $T$  is compatible with the exchange pair  $(X, X^*)$ , but we shall not need this stronger statement.

**Proposition 1.7.** [BMR2] *Let  $H$  be a tame hereditary algebra, and let  $M$  be an indecomposable exceptional object in  $\mathcal{C}$ . Then  $M$  is exchange compatible if and only if  $\text{End}_{\mathcal{C}}(M) \simeq k$ .*

## 2. TAME HEREDITARY ALGEBRAS

In this section we review some facts about tame hereditary algebras, cluster categories and cluster algebras.

We fix a connected extended Dynkin quiver  $Q$ . The category  $\text{mod } kQ$  of finite dimensional modules over the tame hereditary algebra  $H = kQ$  is well understood; see [R]. Let  $\tau$  denote the Auslander-Reiten translate. All indecomposable  $kQ$ -modules  $X$  are either preprojective, i.e.  $\tau^m X$  is projective for some  $m \geq 0$ ; preinjective, i.e.  $\tau^{-m} X$  is injective for some  $m \geq 0$ ; or regular, i.e. not preprojective or preinjective.

The Auslander-Reiten quiver of  $H$  consists of:

- (i) the preprojective component, consisting exactly of the indecomposable preprojective modules;
- (ii) the preinjective component, consisting exactly of the indecomposable preinjective modules;
- (iii) a finite number  $d$  of regular components called non-homogenous (or exceptional) tubes,  $\mathcal{T}_1, \dots, \mathcal{T}_d$ ;
- (iv) an infinite set of regular components called homogenous tubes.

For a fixed tube  $\mathcal{T}$ , there is a number  $m$ , such that  $\tau^m X = X$  for all indecomposable objects in  $\mathcal{T}$ . The minimal such  $m$  is the *rank* of  $\mathcal{T}$ . If  $m = 1$  then  $\mathcal{T}$  is said to be homogeneous.

We will also use the following facts about maps in  $\text{mod } H$ . Let  $P$  (respectively,  $I$  and  $R$ ) be preprojective (respectively, preinjective and regular) indecomposable modules, and a  $R'$  a regular indecomposable module with  $\mathcal{T}_R \neq \mathcal{T}_{R'}$ . Then we have that  $\text{Hom}_H(I, R) = \text{Hom}_H(I, P) = \text{Hom}_H(R, P) = \text{Hom}_H(R, R') = 0$ .

## 3. THE TRANSJECTIVE COMPONENT

We will call an indecomposable object in the cluster category *transjective* if it is not induced by a regular module. Note that the transjective objects form a component of the Auslander-Reiten quiver of  $\mathcal{C}$ . One of our aims is to show that every transjective object has a  $T$ -denominator for tame hereditary algebras. In this section, we show that for this it is sufficient to find one transjective cluster-tilting object all of whose summands have a  $T$ -denominator. Note that the results in this section do not require  $H$  to be tame, but hold for all finite dimensional hereditary algebras.

**Remark 3.1.** *We remark that, given a finite set of indecomposable transjective objects in the cluster category, we can, by replacing the hereditary algebra  $H$  with a derived equivalent hereditary algebra, assume that all of the objects in the set are preprojective [BMRRT, 3.3]. We shall make use of this in what follows.*

We start with the following observation.

**Lemma 3.2.** *Assume  $(X, \tau X)$  is an exchange pair.*

- (a) *The AR-triangle  $\tau X \rightarrow E \rightarrow X \rightarrow$  is an exchange triangle.*
- (b) *Any exceptional object  $M$  is compatible with the exchange pair  $(X, \tau X)$ .*

*Proof.* Part (a) is well-known and follows directly from the fact [BMRRT] that  $\text{Ext}_{\mathcal{C}}^1(X, \tau X) \simeq k$  when  $(X, \tau X)$  is an exchange pair.

For part (b) we can assume that  $\tau X \rightarrow E \rightarrow X \rightarrow$  is induced by an almost split sequence in  $\text{mod } H'$ , by Remark 3.1.  $\mathcal{C}_H = \mathcal{C}_{H'}$ . Then we use [BMR2, 5.1] to obtain that  $\text{Hom}_{\mathcal{C}}(M, \_)$  applied to the AR-triangle  $\tau X \rightarrow E \rightarrow X \rightarrow$  gives an exact sequence. The claim then follows from Proposition 1.6.  $\square$

The following summarizes some facts that will be useful later.

**Proposition 3.3.** *Let  $H$  be a hereditary algebra and  $U$  a tilting  $H$ -module.*

- (a) *If  $U$  is a tilting module such that  $U \not\cong H$  then there is an indecomposable direct summand  $U_i$  of  $U$  which is generated by  $\bar{U} = U/U_i$ .*
- (b) *Furthermore, if  $\bar{U} = U/U_i$  generates  $U_i$ , and  $B \rightarrow U_i$  is the (necessarily surjective) minimal right add  $\bar{U}$ -approximation of  $U_i$  and*

$$0 \rightarrow U^* \rightarrow B \rightarrow U_i \rightarrow 0 \quad (5)$$

*is the induced exact sequence in  $\text{mod } H$  then the  $H$ -module  $\bar{U} \amalg U^*$  is a tilting module in  $\text{mod } H$ .*

- (c) *The exact sequence (5) induces an exchange triangle in  $\mathcal{C}_H$ .*
- (d) *If  $U$  is preprojective, then so is  $U^*$ .*

*Proof.* Part (a) is a theorem of Riedtmann and Schofield [RS]. Part (b) is a special case of a theorem by Happel and Unger [HU]. Part (c) is contained in [BMRRT] and part (d) is obvious.  $\square$

The following is also well-known and holds for any finite dimensional hereditary algebra  $H$ . Note that for  $H$  of finite representation type, all modules are by definition preprojective.

**Lemma 3.4.** *For every preprojective tilting module  $U$  in  $\text{mod } H$  there is a finite sequence of preprojective tilting modules*

$$U = W_0, W_1, W_2, \dots, W_r = H,$$

*and exact sequences*

$$0 \rightarrow M_j^* \rightarrow B_j \rightarrow M_j \rightarrow 0 \quad (6)$$

*with  $B_j \rightarrow M_j$  a minimal right add  $W_j/M_j$ -approximation of the indecomposable direct summand  $M_j$  of  $W_j$ , and*

$$W_{j+1} = (W_j/M_j) \amalg M_j^*.$$

*Proof.* We use the fact that the preprojective component is directed, so there is an induced partial order on the indecomposable modules, generated by  $X \preceq Y$  if  $\text{Hom}(X, Y) \neq 0$ . For the above exchange sequences we have  $M_j^* \preceq M_j$ . The result now follows directly from Proposition 3.3.  $\square$

Next we consider transjective exchange pairs.

**Lemma 3.5.** *Let  $(X, X^*)$  be an exchange pair, where both  $X$  and  $X^*$  are transjective. Then any regular indecomposable exceptional  $M$  is compatible with  $(X, X^*)$ .*

*Proof.* We choose a hereditary algebra  $H'$  derived equivalent to  $H$  such that both  $X$  and  $X^*$  correspond to preprojective  $H'$ -modules (see Remark 3.1). Hence one of the exchange triangles, say

$$X^* \rightarrow B \rightarrow X \rightarrow$$

is induced by an short exact sequence, by [BMRRT]. It is clear that the middle term  $B$  is also induced by a preprojective module. Note that we have  $\mathcal{C}_H \simeq \mathcal{C}_{H'}$ .

We want to show that we get a short exact sequence

$$0 \rightarrow \text{Hom}_{\mathcal{C}}(M, X^*) \rightarrow \text{Hom}_{\mathcal{C}}(M, B) \rightarrow \text{Hom}_{\mathcal{C}}(M, X) \rightarrow 0. \quad (7)$$

Since there is a path of  $H'$ -maps from  $X^*$  to  $X$  in the preprojective component of  $H'$ , and this component is directed, we have that there is no  $H'$ -map  $X \rightarrow \tau X^*$ . Hence the nonzero map  $X \rightarrow \tau X^*$  induced from the exchange triangle is an  $F' = F_{H'}$ -map. Any map  $M \rightarrow X$  is also an  $F'$ -map, using that there are no  $H'$ -maps from regular objects to preprojective objects. But any composition of two  $F'$ -maps is zero. Hence every map  $M \rightarrow X$  will factor through  $B \rightarrow X$ , so the sequence (7) is right exact.

Assume there is a map  $M \rightarrow X^*$ . Then this map must be an  $F'$ -map. Assume the composition  $M \rightarrow X^* \rightarrow B$  is zero, so that  $M \rightarrow X^*$  factors through  $\tau^{-1}X \rightarrow X^*$ .

$$\begin{array}{ccccc} & & M & & \\ & \swarrow & \downarrow & & \\ \tau^{-1}X & \longrightarrow & X^* & \longrightarrow & B \longrightarrow X \end{array}$$

Then both maps  $M \rightarrow \tau^{-1}X$  and  $\tau^{-1}X \rightarrow X^*$  are  $F'$ -maps, and hence the composition is zero. Hence the map  $M \rightarrow X^*$  is zero, and we have shown left-exactness of (7). This finishes the proof by Proposition 1.6.  $\square$

A *slice* in  $\text{mod } H$  (see [R]), is a tilting module  $V$  with a hereditary endomorphism ring. Note that  $\text{End}_{\mathcal{C}}(V)$  is hereditary if and only if  $\text{End}_H(V)$  is hereditary by [ABS].

**Lemma 3.6.** *Assume there is a slice  $V = \coprod_i V_i$  such that each indecomposable direct summand  $V_i$  has a  $T$ -denominator. Then every transjective indecomposable object has a  $T$ -denominator.*

*Proof.* This follows from combining Lemma 3.2 with Proposition 1.6.  $\square$

**Lemma 3.7.** *Assume there is a transjective cluster-tilting object  $U = \coprod_i U_i$  such that each indecomposable direct summand  $U_i$  has a  $T$ -denominator. Then there is a slice  $V = \coprod_i V_i$  such that each indecomposable direct summand  $V_i$  has a  $T$ -denominator.*

*Proof.* We choose a hereditary algebra  $H'$  derived equivalent to  $H$ , so that all the  $U_i$  are preprojective modules in  $\text{mod } H'$  and hence  $U$  is a preprojective tilting module in  $\text{mod } H'$  (see Remark 3.1)

It is clear that each  $W_j$  in Lemma 3.4 is a cluster-tilting object in  $\mathcal{C}_H$ , and that the object  $H'$  forms a slice in  $\mathcal{C}_H$ . Also it is clear that the short exact sequences (6) are exchange triangles in  $\mathcal{C}_H = \mathcal{C}_{H'}$ , with transjective end-terms. So the claim follows from Lemma 3.5 and Proposition 1.6.  $\square$

We can now state the main result of this section.

**Proposition 3.8.** *Assume that there is a transjective cluster-tilting object  $U = \coprod_i U_i$  such that each indecomposable direct summand  $U_i$  has a*



*T-denominator.* Then every transjective indecomposable object has a *T-denominator*.

*Proof.* This follows directly from combining Lemmas 3.6 and 3.7.  $\square$

#### 4. WINGS

For this section assume that  $H$  is a tame hereditary algebra. We state some properties and results concerning regular objects in the cluster category of  $H$ .

Recall that a module  $M$  over an algebra  $A$  is known as a *brick* if it is exceptional and  $\text{End}_A(M) = k$ . In fact, it is known that if  $A$  is hereditary, every exceptional  $A$ -module is a brick. We say that an object  $M$  in the cluster category  $\mathcal{C}$  is a  *$\mathcal{C}$ -brick* if  $M$  is exceptional with  $\text{End}_{\mathcal{C}}(M) = k$ . The following lemma summarizes some well-known facts, including the fact that there are bricks in the cluster category of  $H$  which are not  $\mathcal{C}$ -bricks.

**Lemma 4.1.** *Let  $M, N$  be regular exceptional indecomposable modules in a tube  $\mathcal{T}$  of rank  $t > 1$  in  $\mathcal{C}_H$ .*

- (a) [BMR2] *The object  $M$  is not a  $\mathcal{C}$ -brick if and only if q.l.  $M = t - 1$*
- (b) *Any cluster-tilting object in  $\mathcal{C}_H$  contains at most one object from each tube which is not a  $\mathcal{C}$ -brick.*
- (c) *If q.l.  $M = t - 1$  then the following are equivalent:*
  - (i)  $\text{Hom}_H(M, N) \neq 0$
  - (ii)  $\dim \text{Hom}_H(M, N) = 1$
  - (iii)  $\dim \text{Hom}_{\mathcal{C}}(M, N) = 2$
  - (iv)  $N \notin \mathcal{W}_{\tau M}$

*Proof.* For (c), see [R] for the fact that  $\dim \text{Hom}_H(M, N) \leq 1$ , and the fact that  $\text{Hom}_H(M, N) \neq 0$  if and only if  $\text{Hom}_H(N, \tau^2 M) \neq 0$  if and only if  $N \notin \mathcal{W}_{\tau M}$ . We have

$$\text{Hom}_{\mathcal{C}}(M, N) = \text{Hom}_H(M, N) \amalg \text{Hom}_{\mathcal{D}}(M, \tau^{-1}N[1])$$

and

$$\text{Hom}_{\mathcal{D}}(M, \tau^{-1}N[1]) \simeq D \text{Hom}_{\mathcal{D}}(N, \tau^2 M),$$

so the equivalence in (c) follows and (a) follows.

Part (b) is well-known and easy to see.  $\square$

Let  $\mathcal{W}_M$  be the full category of subfactors of a regular exceptional indecomposable module  $M$  in  $\mathcal{T}_M$ . This is called the *wing* of  $M$ . Suppose that q.l.  $M = t$ . We consider  $\mathcal{W}_M$  as an abelian category equivalent to  $\text{mod } \Lambda_t$ , where  $\Lambda_t$  is the hereditary algebra given as the path algebra of a quiver of Dynkin type  $A_t$ , with linear orientation; see [R]. The module  $M$  is a projective and injective object in  $\mathcal{W}_M$ , and a tilting object in  $\mathcal{W}_M$  has exactly  $t$  indecomposable direct summands. The following is well-known by [S].

**Lemma 4.2.** *Assume that a cluster-tilting object  $T$  in  $\mathcal{C}_H$  has a regular summand  $M$ . Then the summands of  $T$  lying in  $\mathcal{W}_M$  form a tilting object in  $\mathcal{W}_M$ .*

We recall the notion of a Bongartz complement:

**Lemma 4.3.** *Let  $N$  be a partial tilting module. Then there exists a complement  $E$ , known as the Bongartz complement of  $N$ , with the following properties:*

- (a) *There is a short exact sequence  $0 \rightarrow H \rightarrow E_N \rightarrow N \rightarrow 0$  with  $E_N$  in  $\text{add } E$ .*
- (b) *The module  $E$  satisfies the following properties*
  - (B1)  $\text{Ext}_H^1(N, A) = 0$  implies  $\text{Ext}_H^1(E, A) = 0$  for any  $A$  in  $\text{mod } H$ .
  - (B2)  $\text{Hom}_H(N, E) = 0$ .
- (c) *If a complement  $E'$  of a partial tilting module  $X$  satisfies (B1) and (B2), then  $E' \simeq E$ , where  $E$  is the Bongartz complement.*

*Proof.* See [Bo] for (a) and [Ha] for (b) and (c).  $\square$

We are especially interested in the Bongartz complements of certain regular modules.

**Lemma 4.4.** *Let  $X = X_t$  be an exceptional regular indecomposable module with  $\text{q.l. } X = t$ . For  $i = 1, \dots, t-1$ , let  $X_i$  be the regular indecomposable exceptional module such that there is an irreducible monomorphism  $X_i \rightarrow X_{i+1}$ . Then there is a preprojective module  $Q$  such that:*

- (a) *The Bongartz complement of  $X = X_t$  is  $X_1 \amalg \dots \amalg X_{t-1} \amalg Q$ .*
- (b) *The Bongartz complement of  $\widehat{X} = X_1 \amalg \dots \amalg X_{t-1} \amalg X_t$  is  $Q$ .*
- (c) *All partial tilting modules  $Y$  such that  $Y$  is a tilting object in  $\mathcal{W}_X$  have Bongartz complement  $Q$ .*

*Proof.* For (a), first note that  $\text{Ext}_H^1(X, \tau A) = 0$  while  $\text{Ext}_H^1(A, \tau A) \neq 0$  for any indecomposable module  $A$  which is either preinjective or regular with  $\mathcal{T}_A \neq \mathcal{T}_X$ . Hence by (B1) the summands in  $Q$  are either preprojective or regular and lie in  $\mathcal{T}_X$ . The property (B2) shows that any regular summand of the Bongartz complement  $E$  of  $X$  must be in  $\mathcal{W}_{\tau X}$ , by Lemma 4.1. The fact that  $E$  is a complement implies that any regular summand must be in  $\mathcal{W}_{X'}$ , where  $X' \rightarrow X$  is an irreducible monomorphism, since an object  $Z$  in  $\mathcal{W}_{\tau X} \setminus \mathcal{W}_{X'}$  has  $\text{Ext}(X, Z) \neq 0$ . We claim that for any indecomposable regular summand  $E'$  of  $E$  there is a monomorphism  $E' \rightarrow X$ . Assume  $E'$  is an indecomposable regular summand of  $E$ . Then, if  $E'$  is in  $\mathcal{W}_{X'}$ , but there is no monomorphism to  $X$ , the module  $\tau E'$  will satisfy  $\text{Ext}^1(X, \tau E') = 0$ , while  $\text{Ext}^1(E', \tau E') \neq 0$ , a contradiction to (B1). Since  $X \amalg E$  is a cluster-tilting object in  $\mathcal{C}$ , it follows from Lemma 4.2 that all indecomposable regular objects in the tube of  $X$  with monomorphisms to  $X$  are summands of  $E$ .

Part (b) is easily verified, noting that (B1) and (B2) are satisfied.

For (c) we show that if a module  $A$  satisfies  $\text{Ext}_H^1(Y, A) = 0$ , then it satisfies  $\text{Ext}_H^1(\widehat{X}, A) = 0$ . Then it follows that  $\text{Ext}_H^1(Q, A) = 0$ , which implies that  $Q$  satisfies (B1); (B2) is clearly satisfied.

To see that  $\text{Ext}_H^1(\widehat{X}, A) = 0$  we use that  $\mathcal{W}_X$  is equivalent to  $\text{mod } \Lambda_t$ , where  $\Lambda_t$  is the path algebra of the Dynkin quiver  $A_t$  with linear orientation. Now let  $Y_i$  be a direct summand in  $Y$  which is generated by  $Y/Y_i$ , and consider the exact sequence  $0 \rightarrow Y^* \rightarrow B \rightarrow Y \rightarrow 0$ , where  $B \rightarrow Y$  is the minimal right  $\text{add } Y/Y_i$ -approximation. Then  $\text{Ext}_H^1(Y^*, A) = 0$ , since we have an epimorphism  $\text{Ext}_H^1(B, A) \rightarrow \text{Ext}_H^1(Y^*, A)$ . Iterating this sufficiently

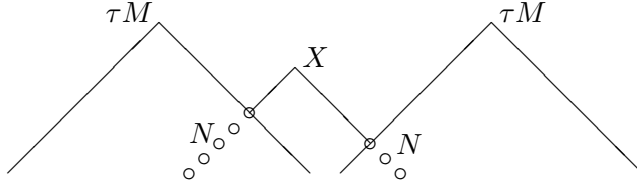


FIGURE 1. A complement  $N$  of  $X$  in  $\mathcal{W}_X$  with summands (indicated by  $\circ$ ) in  $\mathcal{W}_{\tau M}$ : see Lemma 4.5(a).

many times, which is possible by Lemma 3.4, we get that  $\text{Ext}_H^1(\widehat{X}, A) = 0$ .  $\square$

**Lemma 4.5.** *Let  $\mathcal{T}$  be a tube of rank  $t + 1$  and  $M$  an exceptional object in  $\mathcal{T}$  which is not a  $\mathcal{C}$ -brick. Let  $X = X_s$  be an exceptional indecomposable with q.l.  $X = s \leq t$  such that  $X \notin \mathcal{W}_{\tau M}$ .*

- (a) *There is a complement  $N$  of  $X$  in  $\mathcal{W}_X$  all of whose summands lie in  $\mathcal{W}_{\tau M}$ .*
- (b) *The partial tilting module  $X \amalg U$  has a preprojective complement  $Q$  which generates  $X$ .*

*Proof.* See Figure 1 for a pictorial representation of this lemma. For (a) consider the relative projective tilting module in  $\mathcal{W}_X$  given by  $X_1 \amalg \cdots \amalg X_{s-1} \amalg X_s$ , with q.l.  $X_j = j$ . If  $X_{s-1} \notin \mathcal{W}_{\tau M}$ , consider the non-split exact sequence  $0 \rightarrow X_{s-1} \rightarrow X \rightarrow X'_{s-1} \rightarrow 0$ . We claim that  $X'_{s-1}$  is in  $\mathcal{W}_{\tau M}$ . For this, apply  $\text{Hom}_H(M, \_)$  to the above exact sequence. Since by assumption  $\text{Hom}_H(M, X_{s-1}) \neq 0$ , we have that  $\text{Hom}_H(M, X_{s-1}) \rightarrow \text{Hom}_H(M, X)$  is surjective. The map  $(\text{Ext}_H^1(M, X_{s-1}) \rightarrow \text{Ext}_H^1(M, X)) \simeq (D \text{Hom}_H(X_{s-1}, \tau M) \rightarrow D \text{Hom}_H(X, \tau M))$  is a monomorphism, since

$$\text{Hom}_H(X, \tau M) \rightarrow \text{Hom}_H(X_{s-1}, \tau M)$$

is an epimorphism. The last statement follows since  $\tau M$  is not a factor of  $X_{s-1}$ .

We also claim that  $X'_{s-1}$  is a complement of  $X_1 \amalg \cdots \amalg X_{s-2} \amalg X_s$  in  $\mathcal{W}_X$ . This follows from the fact that the map  $X_{s-1} \rightarrow X$  is a minimal left add  $X_1 \amalg \cdots \amalg X_{s-2} \amalg X_s$ -approximation, together with Proposition 3.3.

Now, if necessary, we exchange  $X_{s-2}$  using the minimal add  $X_1 \amalg \cdots \amalg X_{s-3} \amalg X'_{s-1} \amalg X_s$ -approximation  $X_{s-2} \rightarrow X$ . The same argument as above shows that the cokernel of this map gives us a complement in  $\mathcal{W}_{\tau M}$ . We iterate this at most  $s - 1$  times, until we obtain a complement

$$N = X_1 \amalg \cdots \amalg X_k \amalg X'_{k+1} \amalg \cdots \amalg X'_{s-1}$$

for  $X$  in  $\mathcal{W}_X$ , with  $0 \leq k \leq s - 1$ , all of whose summands lie in  $\mathcal{W}_{\tau M}$ , as required.

For (b), let  $Q$  be the Bongartz complement in  $\text{mod } H$  of the partial tilting  $H$ -module  $X_1 \amalg \cdots \amalg X_{s-1} \amalg X_s$ , and apply Lemma 4.4. By Lemma 4.3(a),  $Q$  generates  $N$ , and thus, in particular, it generates  $X$ .  $\square$

## 5. THE MAIN RESULT

In this section, we show the main theorem. The proof will follow from a series of lemmas. Throughout this section, let  $T$  be a cluster-tilting object

in the cluster category  $\mathcal{C}_H$  of a tame hereditary algebra  $H$ . We assume that  $T$  has a summand which is not a  $\mathcal{C}$ -brick. We have the following preliminary results.

**Lemma 5.1.** *Let  $Z$  be an exceptional indecomposable regular module. Let  $X \amalg Y$  be a tilting object in  $\mathcal{W}_Z$ , with  $X$  indecomposable. Assume  $U \amalg X \amalg Y$  is a tilting module in  $\text{mod } H$ , where  $U$  has no preinjective summands.*

- (a) *Let  $B \rightarrow X$  be the minimal right  $\text{add } Y$ -approximation in  $\mathcal{W}_Z$  and  $0 \rightarrow X^* \rightarrow B \rightarrow X \rightarrow 0$  be the exchange sequence in  $\mathcal{W}_Z$ . Then  $B \rightarrow X$  is a right  $\text{add } U \amalg Y$ -approximation.*
- (b) *Let  $X \rightarrow B'$  be the minimal left  $\text{add } Y$ -approximation in  $\mathcal{W}_Z$  and  $0 \rightarrow X \rightarrow B' \rightarrow X^* \rightarrow 0$  be the exchange sequence in  $\mathcal{W}_Z$ . Then  $X \rightarrow B'$  is a left  $\text{add } U \amalg Y$ -approximation.*

*Proof.* Let  $U = U_p \amalg U_r$  where  $U_p$  is preprojective and  $U_r$  is regular. By assumption  $U_r$  has no summands in  $\mathcal{W}_Z$ .

We have  $\text{Hom}_H(U_p, B) \rightarrow \text{Hom}_H(U_p, X)$  is surjective since  $\text{Ext}_H^1(U_p, X^*) \simeq D \text{Hom}_H(\tau^{-1} X^*, U_p) = 0$ .

We claim that  $\text{Hom}_H(U_r, B) \rightarrow \text{Hom}_H(U_r, X)$  is also surjective. For this note that there is an indecomposable direct summand  $B'$  in  $B$  such that the restriction  $B' \rightarrow X$  is surjective. Let  $U'_r$  be a summand in  $U_r$  such that  $\text{Hom}_H(U'_r, X) \neq 0$ . By assumption  $\text{Hom}_H(U'_r, \tau X) = 0$ , since  $\text{Hom}_H(U'_r, \tau X) \simeq D \text{Ext}_H^1(X, U'_r)$ .

Since  $U'_r$  is not in  $\mathcal{W}_Z$ , it follows that any non-zero map  $U'_r \rightarrow B'$  is an epimorphism, and hence factors through  $B' \rightarrow X$ , and the claim follows. Hence  $B \rightarrow X$  is a minimal right  $\text{add}(U \amalg Y)$ -approximation. This completes the proof of (a). The proof of (b) is similar.  $\square$

**Lemma 5.2.** *Let  $\mathcal{T}$  be a tube such that  $T$  has a summand  $M$ , lying in  $\mathcal{T}$ . By Lemma 4.2, we have that  $\text{add } \tau T \cap \mathcal{W}_{\tau M} = \text{add } \tau T'$  for a tilting object  $\tau T'$  in  $\mathcal{W}_{\tau M}$ . Let  $T = T' \amalg T''$ . Then we have:*

- (a) *All tilting objects in  $\mathcal{W}_{\tau M}$  are complements of  $\tau T''$ .*
- (b) *All objects in  $\mathcal{W}_{\tau M}$  have a  $T$ -denominator.*

*Proof.* Note that there is a hereditary algebra  $H'$ , with  $\mathcal{C}_{H'} = \mathcal{C}_H$ , such that  $\tau T''$  as a  $H'$ -module has only regular and preprojective direct summands (see Remark 3.1). Assume q.l.  $M \leq t$ , and that the rank of  $\mathcal{T}$  is  $t + 1$ . Let  $U = \tau T' = \tau N_1 \amalg \cdots \amalg \tau N_{t-1} \amalg \tau M$  be the tilting object in  $\mathcal{W}_{\tau M}$ .

Using Proposition 3.3 and Lemma 3.4, we have that all tilting objects in  $\mathcal{W}_{\tau M}$  can be reached from  $U$  by a finite number of exchanges, given by exchange sequences in  $\mathcal{W}_{\tau M}$ . Using Lemma 5.1 these exchange sequences are also exchange sequences in  $\text{mod } H'$  and hence in  $\mathcal{C}_{H'} = \mathcal{C}_H$ . This shows (a). For (b) it suffices to show that each such exchange pair is compatible with  $T$ . Consider the exchange triangle

$$X' \rightarrow \bar{X} \rightarrow X'' \rightarrow . \quad (8)$$

By Proposition 1.7, the pair  $(X', X'')$  is compatible with all summands in  $T$  which are  $\mathcal{C}$ -bricks. It is clearly compatible with any regular summand  $T_j$  of  $T$  with  $\mathcal{T}_{T_j} \neq \mathcal{T}$  which is not a  $\mathcal{C}$ -brick, since  $\text{Hom}(T_j, \cdot)$  vanishes on all terms of the sequence. By Lemma 4.1(a) we only need to consider compatibility with  $M$  in case q.l.  $M = t$ . But, since the exchange triangle (8) lies inside

$\mathcal{W}_{\tau M}$ , we see that the  $\text{Hom}(M, \ )$  vanishes when applied to (8). Since  $T$  has at most one indecomposable summand in a given tube of quasilength one less than the rank of the tube (by Lemma 4.1(b)), this finishes the proof of (b).  $\square$

**Lemma 5.3.** *Let  $X$  be an exceptional regular indecomposable object of  $\mathcal{C}$  which is a  $\mathcal{C}$ -brick.*

- (a) *An exchange pair  $(X, Z)$  is compatible with any regular object  $M$  for which either  $M$  is a  $\mathcal{C}$ -brick, or  $\mathcal{T}_M \neq \mathcal{T}_X$ , or  $X \in \mathcal{W}_{\tau M'}$ , where  $M' \rightarrow M$  is an irreducible monomorphism.*
- (b) *There is an exchange triangle of the form  $Y \rightarrow Q \amalg X' \rightarrow X \rightarrow$  where  $X' \rightarrow X$  is an irreducible monomorphism in case q.l.  $X > 1$  and  $X' = 0$  otherwise, with the property that  $Y$  and  $Q$  are transjective.*

*Proof.* (a) If  $M$  is a  $\mathcal{C}$ -brick then this holds by Proposition 1.7. For the other cases note that  $\text{Hom}(M, X) = 0 = \text{Hom}(M, \tau^{-1}X)$ , and hence when  $\text{Hom}(M, \ )$  is applied to the exchange triangle  $Z \rightarrow Q' \rightarrow X \rightarrow$ , one obtains a short exact sequence.

For (b), let  $E$  be the Bongartz complement of the  $H$ -module  $X$ , and consider the minimal right add  $E$ -approximation  $E' \rightarrow X$  (as  $H$ -module). By Lemma 4.3,  $E$  generates  $X$ , so the approximation is surjective, and we have a short exact sequence  $0 \rightarrow Y \rightarrow E' \rightarrow X \rightarrow$  and thus an induced approximation triangle,  $Y \rightarrow E' \rightarrow X \rightarrow$  in  $\mathcal{C}$ . By Lemma 4.4(a), we have that  $X'$  is the only regular summand of  $E'$  and the other summands are preprojective. Since  $E' \rightarrow X$  is surjective, we also have, using Lemma 4.4(a), that  $E'$  has a preprojective summand, and the claim follows.  $\square$

We now deal with the transjective objects.

**Proposition 5.4.** *All transjective objects have a  $T$ -denominator.*

*Proof.* By Proposition 3.8 it is sufficient to show that there is one transjective cluster-tilting object all of whose indecomposable direct summands have  $T$ -denominators. Without loss of generality we can assume that  $T$  has at least one indecomposable direct summand which is not a  $\mathcal{C}$ -brick.

Assume  $T = Q \amalg R$ , where  $Q$  is transjective and  $R$  is regular. Then, using Lemma 4.2, there are indecomposable summands  $M_1, \dots, M_z$  of  $R$  such that each summand of  $R$  lies in one of the wings  $\mathcal{W}_{M_i}$ . We choose a minimal such set of summands. Since  $\text{Ext}_{\mathcal{C}}^1(M_i, A) \neq 0$  for any object  $A$  whose wing overlaps  $\mathcal{W}_{M_i}$ , any two of the  $\mathcal{W}_{M_i}$  must be either equal or disjoint.

By definition, all summands of  $\tau T$  have  $T$ -denominators. By Lemma 5.2, we can, for each  $i$ , replace the summands of  $\tau T$  in  $\mathcal{W}_{\tau M_i}$  with the indecomposable objects in the tube of  $M_i$  which have a monomorphism to  $\tau M_i$ . We obtain a new cluster-tilting object  $U = (\amalg_{i=1}^z \tau M_i) \amalg U'$  all of whose indecomposable direct summands have  $T$ -denominators.

Fix  $N = M_1$  of quasilength  $t$  and let  $N_1, N_2, \dots, N_t = N$  be the indecomposable objects in  $\mathcal{T}_N$  with monomorphisms to  $N$ , where q.l.  $(N_i) = i$  for all  $i$ . Then we can write  $U = (\amalg_{i=1}^t \tau N_i) \amalg Y$ . We claim that, via a sequence of exchanges, the  $\tau N_i$  can be replaced by transjective summands  $Q_i$  which have  $T$ -denominators. When repeating this for  $M_1, M_2, \dots, M_z$ , we

will end up with a transjective cluster-tilting object having  $T$ -denominators as required.

We exchange  $\tau N$  with a complement  $(\tau N)^*$ , via the exchange triangles:

$$\begin{aligned} (\tau N)^* &\rightarrow B \rightarrow \tau N \rightarrow \\ \tau N &\rightarrow B' \rightarrow (\tau N)^* \rightarrow . \end{aligned}$$

**Claim:** The object  $(\tau N)^*$  is transjective.

If  $(\tau N)^*$  is not induced by an  $H$ -module, it is induced by the shift of a projective module, and we are done. So we can assume that  $(\tau N)^*$  is induced by a module. Then one of these two exchange triangles must arise from a short exact sequence of modules.

If it is the first, then clearly  $\text{Hom}_H(X, \tau N) = 0$  for any regular summand  $X$  of  $U$  not in  $\mathcal{T}_N$ . But if  $X$  lies in  $\mathcal{T}_N$  and not in  $\mathcal{W}_{\tau M_1}$ , again  $\text{Hom}_H(X, \tau N) = 0$  since the wings  $\mathcal{W}_{\tau M_i}$  do not overlap (and  $\text{q.l.}(M_i)$  is less than the rank of its tube for all  $i$ ). Let  $N_0 = 0$ . Since  $\tau N_{t-1}$  does not generate  $\tau N_t = \tau M_i$ , it follows that  $B$  has a nonzero preprojective summand, and hence that  $(\tau N)^*$  is preprojective.

If it is the second, then clearly  $\text{Hom}_H(\tau N, X) = 0$  for any regular summand  $X$  of  $U$  not in  $\mathcal{T}_N$ . But if  $X$  lies in  $\mathcal{T}_N$  and not in  $\mathcal{W}_{\tau M_1}$ , again  $\text{Hom}_H(\tau N, X) = 0$  since the wings  $\mathcal{W}_{\tau M_i}$  do not overlap. Since  $\text{Hom}_H(\tau N, \tau N_j) = 0$  for all  $j$ , it follows that  $B'$  has a nonzero preinjective summand, and hence that  $(\tau N)^*$  is preinjective.

Hence, in either case,  $(\tau N)^*$  is transjective. We next show that  $(\tau N)^*$  has a  $T$ -denominator, by considering two cases:

CASE I: We assume first that  $N$  has  $\text{End}(N) = k$ , i.e.  $N$  is a  $\mathcal{C}$ -brick.

Every summand of  $T$  in  $\mathcal{T} = \mathcal{T}_N$  is a  $\mathcal{C}$ -brick (by the choice of the  $M_i$ ), so by Lemma 5.3(a) we obtain that the exchange pair  $(\tau N, (\tau N)^*)$  is compatible with all summands of  $T$ , and hence that  $(\tau N)^*$  has a  $T$ -denominator by Proposition 1.6. We then repeat this procedure for  $\tau N_{t-1}, \dots, \tau N_1$ .

CASE II:  $N$  has  $\text{End}(N) \neq k$ , i.e.  $N$  is not a  $\mathcal{C}$ -brick. Arguing as above, we see that we can exchange  $\tau N$  with a transjective object  $(\tau N)^*$ . Since  $N$  is a summand of  $T$ , we have that  $T$  is compatible with the exchange pair  $(\tau N, (\tau N)^*)$  by definition. So  $(\tau N)^*$  has a  $T$ -denominator by Proposition 1.6. We can then exchange the other summands  $\tau N_{t-1}, \dots, \tau N_1$  with transjectives, all having  $T$ -denominators, as in Case I.

Hence, there is a transjective cluster-tilting object having a  $T$ -denominator, and we are done.  $\square$

**Lemma 5.5.** *Let  $\mathcal{T}$  be a tube such that each direct summand of  $T$  lying in  $\mathcal{T}$  is a  $\mathcal{C}$ -brick, or such that  $\mathcal{T}$  has no summands in  $T$ . Then each exceptional indecomposable object in  $\mathcal{T}$  has a  $T$ -denominator.*

*Proof.* Let  $X$  be an exceptional indecomposable object in  $\mathcal{T}$ . We prove the Lemma by induction on the quasilength of  $X$ .

If  $\text{q.l. } X = 1$ , then by Lemma 5.3(b) there is an exchange triangle  $Y \rightarrow Q \rightarrow X \rightarrow$  with  $Q$  and  $Y$  transjective. By Proposition 1.7, we need only show that  $(Y, X)$  is compatible with any regular non  $\mathcal{C}$ -brick summand  $M$  of  $T$ . But this follows from Lemma 5.3.

Now assume that any exceptional indecomposable object  $Y$  of quasilength less than  $t$  has a  $T$ -denominator. We want to show that the result

also holds for the exceptional indecomposable  $X$  with q.l.  $X = t$ . For this we use Lemma 3.2.  $\square$

It now remains to deal with the exceptional objects which are in  $\overline{\mathcal{W}_{\tau M}}$  for a non  $\mathcal{C}$ -brick summand  $M$  of  $T$ . For this the following lemma is crucial.

**Lemma 5.6.** *For each indecomposable exceptional object  $X$  in  $\overline{\mathcal{W}_{\tau M}}$ , there are exchange sequences*

$$X^* \rightarrow B \rightarrow X \rightarrow$$

and

$$X \rightarrow B' \rightarrow X^* \rightarrow$$

such that

(i)

$$\begin{aligned} \max(\dim \operatorname{Hom}(M, B), \dim \operatorname{Hom}(M, B')) \\ = \dim \operatorname{Hom}(M, X^*) + \dim \operatorname{Hom}(M, X) - 1 \end{aligned}$$

(ii) *The object  $X^*$  and all indecomposable summands of the objects  $B$  and  $B'$  have  $T$ -denominators.*

(iii) *The object  $X^*$  is induced by a preprojective module.*

*Proof.* By Lemma 4.5(a), there is an object  $N$  in  $\mathcal{W}_X$  such that  $N \amalg X$  is a tilting object in the wing  $\mathcal{W}_X$  and all direct summands of  $N$  are in  $\mathcal{W}_{\tau M}$ .

By Lemma 4.5(b), we have that  $N \amalg X$  has a preprojective complement  $Q$  in  $\operatorname{mod} H$ , such that  $Q$  generates  $X$ . Let  $R = Q \amalg N$  and let  $B \rightarrow X$  (respectively,  $X \rightarrow B'$ ) be the minimal right, (respectively, minimal left) add  $R$ -approximations of  $X$ . We claim that the induced exchange triangles satisfy (i), (ii) and (iii).

Consider the exchange triangle

$$X^* \rightarrow B \rightarrow X \rightarrow .$$

Since  $Q$  generates  $X$  in  $\operatorname{mod} H$ , it is clear that this triangle is induced by a short exact sequence in  $\operatorname{mod} H$ , and hence  $X^*$  is induced by a preprojective module (showing (iii)), since  $X^* \rightarrow B$  is nonzero and  $B$  must have a preprojective summand as  $N$  doesn't generate  $X$ .

Apply  $\operatorname{Hom}(M, \_)$  to obtain the long exact sequence

$$(M, \tau^{-1}X) \rightarrow (M, X^*) \rightarrow (M, B) \rightarrow (M, X) \rightarrow (M, \tau X^*).$$

We claim that every  $H$ -map  $\tau M \rightarrow X$  factors through  $B$ . This follows from the configuration of  $M, N$  and  $X$  in the Auslander-Reiten quiver of the tube, noting that  $\operatorname{Hom}_H(\tau M, N) \neq 0$  if and only if  $\operatorname{Hom}(\tau M, X) \neq 0$  (if and only if  $N \neq 0$ ). Figure 2 displays this case, when  $N$  has a summand  $B'$  (occurring in  $B$ ) with  $\operatorname{Hom}_H(\tau M, B') \neq 0$ ; compare with Figure 1. By [BMR2, Lemma 5.1] it follows that  $(M, X^*) \rightarrow (M, B)$  is a monomorphism.

We claim that  $\dim \operatorname{coker}((M, B) \rightarrow (M, X)) = 1$ . By Lemma 4.1, we have that  $\dim \operatorname{Hom}_H(M, X) = 1$  and it is clear that an  $H$ -map  $M \rightarrow X$  will not factor through  $B$ , since  $N$  is in  $\mathcal{W}_{\tau M}$ , and hence  $\operatorname{Hom}_H(M, N) = 0$ , by Lemma 4.1.

By Lemma 4.1 the space of  $F$ -maps  $M \rightarrow X$  is also one-dimensional. We claim that such  $F$ -maps will factor through  $B$ . For this we consider two possible cases: the object  $X^*$  is either induced by a projective  $H$ -module

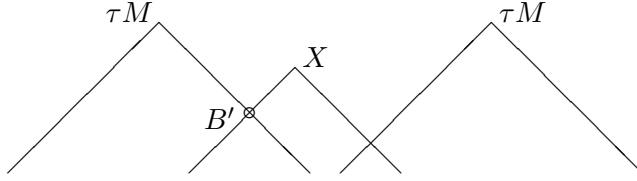


FIGURE 2. A summand  $B'$  of  $N$  with  $\text{Hom}_H(\tau M, B') \neq 0$ : see proof of Lemma 5.6.

$P$  or not. First assume that  $X^*$  is non-projective. Since the composition of two  $F$ -maps is 0, it is clear that all  $F$ -maps  $M \rightarrow X$  will factor through  $B \rightarrow X$ . Hence the claim follows in this case. Now consider the case where  $X^*$  is projective. Then the composition  $M \rightarrow \tau^{-1}X[1] \rightarrow \tau^{-1}(P_i[1])[1]$  is clearly zero, so the claim follows in this case.

We next want to show that when  $\text{Hom}(M, \ )$  is applied to the second exchange triangle

$$X \rightarrow B' \rightarrow X^* \rightarrow,$$

we do not obtain an exact sequence. The map  $X \rightarrow B'$  decomposes into  $X \rightarrow Q_0 \amalg N_0$ , with  $Q_0$  preprojective and  $N_0$  in  $\mathcal{W}_{\tau M}$ . Hence  $X \rightarrow Q_0$  is an  $F$ -map. There is a non-zero  $F$ -map  $M \rightarrow X$  and the composition  $M \rightarrow X \rightarrow B'$  will be zero since  $M \rightarrow X \rightarrow Q_0$  is the composition of two  $F$ -maps and  $\text{Hom}(M, N_0) = 0$ , since  $M \in \mathcal{W}_{\tau M}$ .

Hence we obtain (i), and (ii) follows using Lemmas 3.6 and 5.2(b), using the fact that  $X^*$  and all indecomposable summands of  $B$  and  $B'$  are either transjective or in  $\mathcal{W}_{\tau M}$ .  $\square$

The proof of the following is an adoption of parts the proof of [BMRT, Prop. 3.1]. It completes the proof of our main result, Theorem A.

**Proposition 5.7.** *Let  $\mathcal{T}$  be a tube such that  $T$  has a non  $\mathcal{C}$ -brick summand  $M$ , lying in  $\mathcal{T}$ . Then each object in  $\overline{\mathcal{W}_{\tau M}}$  has a reduced  $T$ -denominator.*

*Proof.* Let  $X^*$  be an indecomposable object in  $\overline{\mathcal{W}_{\tau M}}$ . By Lemma 5.6 there is an indecomposable object  $X$  and exchange triangles

$$X^* \rightarrow B \rightarrow X \rightarrow$$

and

$$X \rightarrow B' \rightarrow X^* \rightarrow$$

such that (i) and (ii) in Lemma 5.6 hold.

We have [BMR1] that

$$x_X x_{X^*} = x_B + x_{B'}. \quad (9)$$

Assume  $M = T_l$ . We need to discuss two different cases.

CASE I: Suppose that neither  $X$  nor  $X^*$  is isomorphic to  $\tau T_i$  for any  $i$ . Let  $B = B_0 \amalg B_1$ , where no summand of  $B_0$  is of the form  $\tau T_i$  for any  $i$ , and  $B_1$  is in add  $\tau T$ . Similarly, write  $B' = B'_0 \amalg B'_1$ .

We then have  $x_B = \frac{f_{B_0} y_{B_1}}{t_{B_0}}$  and  $x_{B'} = \frac{f_{B'_0} y_{B'_1}}{t_{B'_0}}$ .



Let  $m = \frac{\text{lcm}(t_{B_0}, t_{B'_0})}{t_{B_0}}$  and  $m' = \frac{\text{lcm}(t_{B_0}, t_{B'_0})}{t_{B'_0}}$ . We then have:

$$(x_{X^*}) = \frac{x_B + x_{B'}}{x_X} = \frac{(f_{B_0} m y_{B_1} + f_{B'_0} m' y_{B'_1}) / f_X}{\text{lcm}(t_B, t_{B'}) / t_X},$$

using that  $t_B = t_{B_0}$  since  $\text{Hom}_{\mathcal{C}}(T_i, \tau T_j) = 0$  for all  $i, j$ , and similarly  $t_{B'} = t_{B'_0}$ .

Since  $M = T_l$  is a summand in  $T$ , we have by Lemma 5.6 that

$$\begin{aligned} \max(\dim \text{Hom}(T_l, B), \dim \text{Hom}(T_l, B')) \\ = \dim \text{Hom}(T_l, X^*) + \dim \text{Hom}(T_l, X) - 1. \end{aligned}$$

For any other summand of  $T$ , say  $T_i$  with  $i \neq l$ , we have that  $T_i$  is compatible with  $(X, X^*)$ , and hence

$$\begin{aligned} \max(\dim \text{Hom}(T_i, B), \dim \text{Hom}(T_i, B')) \\ = \dim \text{Hom}(T_i, X^*) + \dim \text{Hom}(T_i, X). \end{aligned}$$

We thus obtain:

$$\begin{aligned} t_X t_{X^*} &= \prod y_i^{\dim \text{Hom}_{\mathcal{C}}(T_i, X) + \dim \text{Hom}_{\mathcal{C}}(T_i, X^*)} \\ &= y_l \cdot \prod y_i^{\max(\dim \text{Hom}_{\mathcal{C}}(T_i, B), \dim \text{Hom}_{\mathcal{C}}(T_i, B'))} = y_l \cdot \text{lcm}(t_B, t_{B'}). \end{aligned}$$

Hence

$$x_{X^*} = \frac{(f_{B_0} m y_{B_1} + f_{B'_0} m' y_{B'_1}) / f_X}{t_{X^*} / y_l}. \quad (10)$$

We have that  $m$  and  $m'$  are coprime, by definition of least common multiple. Since  $B$  and  $B'$  have no common direct summands [BMR1, 6.1],  $y_{B_1}$  and  $y_{B'_1}$  are coprime. Suppose that  $m$  and  $y_{B'_1}$  had a common factor  $y_i$ . Then we would have a summand  $Z$  of  $B'_0$  such that  $\text{Hom}_{\mathcal{C}}(T_i, Z) \neq 0$ , and  $\tau T_i$  was a summand of  $B'$ . But then

$$\text{Ext}_{\mathcal{C}}^1(Z, \tau T_i) \simeq D \text{Hom}_{\mathcal{C}}(\tau T_i, \tau Z) \simeq D \text{Hom}_{\mathcal{C}}(T_i, Z) \neq 0.$$

This contradicts the fact that  $B'$  is the direct sum of summands of a cluster-tilting object. Therefore  $m$  and  $y_{B'_1}$  are coprime, and similarly  $m'$  and  $y_{B_1}$  are coprime. It follows that  $m y_{B_1}$  and  $m' y_{B'_1}$  are coprime.

It follows from our assumptions that  $f_{B_0}(e_i) > 0$  and  $f_{B'_0}(e_i) > 0$  for each  $i \in \{1, 2, \dots, n\}$ . It is clear that  $(m y_{B_1})(e_i) \geq 0$  and  $(m' y_{B'_1})(e_i) \geq 0$ . Using that  $m y_{B_1}$  and  $m' y_{B'_1}$  are coprime, it follows that these two numbers cannot simultaneously be zero, so  $(f_B m y_{B_1} + f_{B'} m' y_{B'_1})(e_i) > 0$ . Hence  $f_B m y_{B_1} + f_{B'} m' y_{B'_1}$  satisfies the positivity condition. By assumption,  $f_X$  also satisfies the positivity condition.

By the Laurent phenomenon [FZ1, 3.1],  $x_{X^*}$  is a Laurent polynomial in  $y_1, y_2, \dots, y_n$ . Clearly  $t_{X^*} / y_l$  is also a Laurent polynomial. Hence  $u = (f_B m y_{B_1} + f_{B'} m' y_{B'_1}) / f_X = \frac{x_{X^*} t_{X^*}}{y_l}$  is also a Laurent polynomial. Since  $u$  is defined at  $e_i$  for all  $i$ , it must be a polynomial. By the above,  $u$  satisfies the positivity condition.

We have that  $y_l$  divides  $t_{X^*} = \prod y_i^{\dim \text{Hom}_{\mathcal{C}}(T_i, X^*)}$ , since  $\dim \text{Hom}_{\mathcal{C}}(T_l, X^*) = 2$ . Hence we get that  $t_{X^*} / y_l$  is a monomial. This finishes the proof in Case (I).

CASE II: Assume that  $X \simeq \tau T_i$  for some  $i$ . Note that  $i \neq l$ , since  $X$  and hence  $T_i$  is transjective, while  $T_l$  is regular.

Since  $\text{Ext}_{\mathcal{C}}^1(T_r, T_s) = 0$  for all  $r, s$ , we have that  $X^* \not\simeq \tau T_j$  for any  $j$ .

Using Proposition 1.6 and Lemma 5.6, we have

$$\begin{aligned} \dim \text{Hom}_{\mathcal{C}}(T_j, X) + \dim \text{Hom}_{\mathcal{C}}(T_j, X^*) \\ = \max(\dim \text{Hom}_{\mathcal{C}}(T_j, B), \dim \text{Hom}_{\mathcal{C}}(T_j, B')) + \epsilon_j, \end{aligned}$$

where

$$\epsilon_j = \begin{cases} 1 & \text{if } j = i \text{ or } j = l \\ 0 & \text{otherwise} \end{cases}.$$

As in Case (I), but using that  $x_X = y_i$  (as  $X = \tau T_i$ ), we obtain the expression

$$x_{X^*} = \frac{(f_{B_0} m y_{B_1} + f_{B'_0} m' y_{B'_1}) / f_X}{\text{lcm}(t_B, t_{B'}) y_i}.$$

Using  $\text{lcm}(t_B, t_{B'}) = t_X t_{X^*} y_i^{-1} y_l^{-1}$ , we get

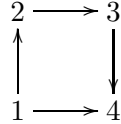
$$x_{X^*} = \frac{(f_{B_0} m y_{B_1} + f_{B'_0} m' y_{B'_1}) / f_X}{t_{X^*} / y_l}.$$

As in Case (I), we get that the numerator satisfies positivity and is a polynomial, and that  $t_{X^*} y_l^{-1}$  is a monomial. The proof is complete.  $\square$

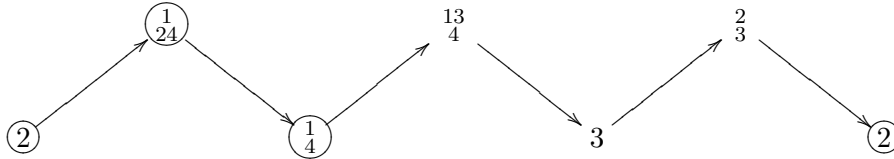
## 6. AN EXAMPLE

We give a small example illustrating the main theorem.

Let  $Q$  be the extended Dynkin quiver



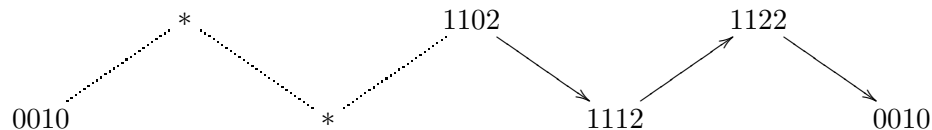
and let  $H = kQ$  be the path algebra. Then  $H$  is a tame hereditary algebra where the AR-quiver has one exceptional tube  $\mathcal{T}$ , which is of rank 3. The (exceptional part of) the AR-quiver of  $\mathcal{T}$  is as follows, where the composition factors (in radical layers) of indecomposable modules are given.



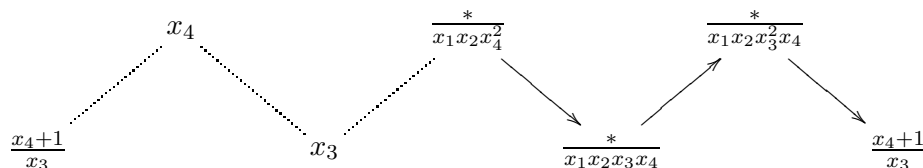
Let  $P_i = He_i$  denote the indecomposable projective  $H$ -modules. Let  $T = T_1 \amalg T_2 \amalg T_3 \amalg T_4 = \tau^{-1} P_4 \amalg \tau^{-1} P_1 \amalg 3 \amalg \begin{smallmatrix} 13 \\ 4 \end{smallmatrix}$ . It is easily verified that this is a cluster-tilting object. The encircled modules in the above figure are those which are in  $\mathcal{W}_{\tau T_4}$ .

For each exceptional object  $Y$  in the tube  $\mathcal{T}$ , we give the dimension vector of  $\text{Hom}_{\mathcal{C}}(T, Y)$  over  $\text{End}_{\mathcal{C}}(T)$ . Note that  $\text{Hom}_{\mathcal{C}}(T, \tau T_3) = 0 =$

$\text{Hom}_{\mathcal{C}}(T, \tau T_4)$ .



We consider the initial seed  $\{x_1, \dots, x_4\}$  where  $x_i = x_{\tau T_i}$ . We give the corresponding cluster variables  $x_Y$  (with most of the numerators skipped).



We observe that the denominators of these cluster variables can be computed from the dimension vectors of the corresponding modules over  $\text{End}_{\mathcal{C}}(T)$ , as described by our main Theorem.

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